

Very Massive Stars in the Local Universe

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Abstract Recent studies have claimed the existence of very massive stars (VMS) up to $300 M_{\odot}$ in the local Universe. As this finding may represent a paradigm shift for the canonical stellar upper-mass limit of $150 M_{\odot}$, it is timely to evaluate the physics specific to VMS, which is currently missing. For this reason, we decided to construct a book entailing both a discussion of the accuracy of VMS masses (Martins), as well as the physics of VMS formation (Krumholz), mass loss (Vink), instabilities (Owocki), evolution (Hirschi), and fate (theory – Woosley & Heger; observations – Smith).

1 Introduction

It has been thought for many years that very massive stars (VMS) with masses substantially larger than $100 M_{\odot}$ may occur more frequently in the early Universe, some few hundred million years after the Big Bang. The reason for the expectation that the first few stellar generations would generally have been more massive is that there was less cooling during the formation process of these metal-poor objects than in today's metal-rich Universe (e.g. Bromm et al. 1999; Abel et al. 2002; Omukai & Palla 2003; Yoshida et al. 2004; Ohkubo et al. 2009).

Furthermore, as radiation-driven winds are thought to be weaker at the lower metal content of the early Universe (e.g. Kudritzki 2002; Vink & de Koter 2005; Krticka & Kubat 2006; Gräfener & Hamann 2008; Muijres et al. 2012), this could imply that the final masses of VMS in the early Universe would be almost equally high as their initial masses. This could then lead to the formation of $10^2 - 10^3 M_{\odot}$ intermediate-mass black holes (IMBHs), with masses in between stellar mass black holes and supermassive black holes of order $10^5 M_{\odot}$ in the centres of galaxies.

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IMBHs have been hypothesized to be the central engines of the ultraluminous x-ray sources (ULXs). Moreover, in a high stellar mass – low mass loss – situation it might become possible to produce pair-instability supernovae (PISNe) in the initial mass range of $140\text{--}260 M_{\odot}$ (Woosley et al. 2002; see also Fowler & Hoyle 1964; Barkat et al. 1967; Bond et al. 1984; Langer et al. 2007; Moriya et al. 2010; Pan et al. 2012; Dessart et al. 2013; Whalen et al. 2013). Such PISNs are very special as just one such explosion could potentially produce more metals than an entire initial mass function (IMF) below it (Langer 2012).

Interestingly, Crowther et al. (2010) re-analyzed the most massive hydrogen- and nitrogen-rich Wolf-Rayet (WNh) stars in the center of R136, the ionizing cluster of the Tarantula nebula in the Large Magellanic Cloud (LMC). The conclusion from their analysis was that stars usually assumed to be below the canonical stellar upper-mass limit of $150 M_{\odot}$ (of e.g. Figer 2005), were actually found to be much more luminous (see also Hamann et al. 2006; Bestenlehner et al. 2011), with initial masses up to $\sim 200\text{--}300 M_{\odot}$. As this finding may represent a paradigm shift for the canonical stellar upper-mass limit of $150 M_{\odot}$, it is timely to discuss the status of the data as well as VMS theory.

Whilst textbooks and reviews have been devoted to the physics of canonical massive single and binary stars (Maeder 2009; Langer 2012) there is as yet no source that specifically addresses the physics unique to VMS. As such objects are in close proximity to the Eddington limit, this is likely to affect both their formation, and via their mass loss also their fates.

2 The role of very massive stars in the Universe

The first couple of stellar generations may be good candidates for the reionization of the Universe (e.g. Haehnelt et al. 2001; Barkana & Loeb 2001; Ciardi & Ferrara 2005; Fan et al. 2006) and their ionizing properties at very low metallicity (Z) may also be able to explain the extreme $\text{Ly}\alpha$ and He II emitting galaxies at high redshift (Malhotra & Rhoads 2002; Kudritzki 2002; Schaerer 2003; Stark et al. 2007; Ouchi et al. 2008).

Notwithstanding the role of the first stars, the interest in the current generation of massive stars has grown as well. Massive stars are important drivers for the evolution of galaxies, as the prime contributors to the chemical and energy input into the interstellar medium (ISM) through stellar winds and supernovae (SNe). A number of exciting developments have taken place in recent years, including the detection of long-duration gamma-ray bursts (GRBs) at redshifts of 9 (e.g. Tanvir et al. 2009), just a few hundred millions years after the Big Bang (Cucchiara et al. 2011). This provides convincing evidence that massive stars are able to form and die massive when the Universe was not yet enriched.

Very massive stars are usually found in and around young massive clusters, such as the Arches cluster in the Galactic centre and the local starburst region R136 in the LMC. Young clusters are also relevant for the unsolved problem of massive star

formation. For decades it was a real challenge to form stars over $10 - 20 M_{\odot}$, as radiation pressure on dust grains might halt and reverse the accretion flow onto the central object (e.g. Yorke & Kruegel 1977; Wolfire & Cassinelli 1987). Because of this issue, theorists have been creative in forming massive stars via competitive accretion and collisions in dense cluster environments (e.g., Bonnell et al. 1998). In more recent times several multi-D simulations have shown that massive stars might form via disk accretion after all (e.g., Krumholz et al. 2009; Kuiper et al. 2010). In the light of recent claims for the existence of VMS in dense clusters, however, the issue of forming VMS in extreme environments is discussed by Mark Krumholz in Chapter 3.

The fact that so many VMS are located within dense stellar clusters still allows for an intriguing scenario in which VMS may originate from collisions of smaller objects (e.g., Portegies Zwart et al. 1999; Gürkan et al. 2004), leading to the formation of VMS up to $1000 M_{\odot}$ at the cluster center, which may produce IMBHs at the end of their lives, but only if VMS mass loss is not too severe (see Belkus et al. 2007, Yungelson et al. 2008, Glebbeek et al. 2009, Pauldrach et al. 2012).

3 Definition of a very massive star

One of the very first questions that arises when one prepares a book on VMS is what actually constitutes a “very” massive star. One may approach this in several different ways.

Theoretically, “normal” massive stars with masses above $\sim 8 M_{\odot}$ are those that produce core-collapse SNe (Smartt et al. 2009), but what happens at the upper-mass end? Above a certain critical mass, one would expect the occurrence of PISNe, and ideally this could be the lower-mass limit for the definition of our VMS. However, in practice this number is not known a priori (due to mass loss), and therefore the initial and final masses are likely not the same. In other words, the initial main-sequence mass for PISN formation is model-dependent, and thus somewhat arbitrary. Furthermore, there is the complicating issue of pulsational pair-instability (PPI) at masses below those of full-fedged PISNe (e.g. Woosley et al. 2007). One could alternatively resort to the mass of the helium (He) core for which stars reach the conditions of electron/positron pair-formation instability. Heger showed this minimum mass to be $\sim 40 M_{\odot}$ to encounter the PPI regime and $\sim 65 M_{\odot}$ to enter the arena of the true PISNe (see also Chatzopoulos & Wheeler 2012).

Another definition could involve the spectroscopic transition between normal main-sequence O-type stars and hydrogen-rich Wolf-Rayet stars (of WNh type), which have also been shown to be core H burning main sequence objects. However, such a definition would be dependent on the mass-loss transition point between O-type and WNh stars, which is set by the transition luminosity (Vink & Gräfener 2012) and is expected to be Z dependent.

For these very reasons, we decided at the joint discussion meeting at the 2012 IAU GA in Beijing to follow a more pragmatic approach, defining stars to be *very* massive when their initial masses are $\simeq 100 M_{\odot}$ (Vink et al. 2013).

4 The very existence of very massive stars

With this definition, the question of whether *very* massive stars exist can easily be answered affirmatively, but the more relevant question during the joint discussion was whether the widely held “canonical” upper-mass limit of $150 M_{\odot}$ has been superseded, as some part of the astronomical community had expressed some skepticism regarding very high masses in R136, in the light of an earlier spectacular claim for the existence of a $2500 M_{\odot}$ star R136 in the 30 Doradus region of the LMC (e.g. Cassinelli et al. 1981). Higher spatial resolution showed that R136 was actually not a single supermassive star, but it eventually revealed a young cluster containing several lower mass objects, including the current record holder R136a1.

Over the last few decades there has been a consensus of a $150 M_{\odot}$ stellar upper mass limit (Weidner & Kroupa 2004; Figer 2005; Oey & Clarke 2005, Koen 2006), albeit the accuracy of these claims was surprisingly low (e.g. Massey 2011). Crowther et al. (2010) re-analyzed the VMS data in R136 claiming that the cluster hosts several stars with masses as high as $200\text{--}300 M_{\odot}$. In addition they performed a sanity check on similar WNh objects in the Galactic starburst cluster NGC 3603. Although these objects were fainter than those in R136, the advantage was the available dynamical mass estimate by Schnurr et al. (2008) of the binary object NGC 3603-A1 with a primary mass of $116 \pm 31 M_{\odot}$. This was deemed important as the least model-dependent way to obtain stellar masses is through the analysis of the light-curves and radial velocities induced by binary motions (see Martins’ Chapter 2).

It could still be argued that the luminosities derived by Crowther et al. are uncertain and that these central WNh stars might in reality involve multiple sources due to insufficient spatial resolution, especially considering that the highest resolution data of the young Galactic Arches cluster with the largest telescope (Keck) only has a limiting resolution of 50 milli-arcsec, and given that R136 is 7 times more distant than the Arches cluster, the achievable resolution if the Arches cluster were in the LMC would mean that R136 would not be resolved. This suggests that we still cannot be 100% certain that the bright WNh stars in R136 could not “break up” into lower-mass objects.

For this reason it was rather relevant that Bestenlehner et al. (2011) found an almost identical twin of R136a3 WNh star in 30 Doradus: VFTS 682. Its key relevance is that it is located in apparent isolation from the R136 cluster, and as a result the chance of line-of-sight contamination is insignificant in comparison to R136. The VFTS 682 object thus offered a second sanity check on the reliability of the luminosities of the R136 core stars. Bestenlehner et al. argued for a high luminosity of $\log(L/L_{\odot}) = 6.5$ with a present-day mass of $150 M_{\odot}$ for VFTS 682, which implies

an initial mass on the zero-age main sequence (ZAMS) higher than the canonical upper-mass limit.

In other words, although one cannot exclude the possibility that the object R136a1 claimed to be $\sim 300 M_{\odot}$ in the R136 cluster might still “dissolve” when higher spatial resolution observations become available, the sanity checks involving binary dynamics and isolated objects make it quite convincing that stars with ZAMS masses at least up to $200 M_{\odot}$ exist.

A more detailed overview of the masses of VMS and the upper end of the IMF will be described in Martins’ Chapter 2.

5 The evolution and fate of very massive stars

Very massive stars are thought to evolve almost chemically homogeneously (Hirschi’s Chapter 6), implying that knowing the exact details of the mixing processes (e.g., rotation, magnetic fields) are less relevant in comparison to their canonical ~ 10 – $60 M_{\odot}$ counterparts. Instead, the evolution and death of VMS is dominated by mass loss.

At some level it does not matter ‘how’ VMS became such massive objects. First of all we do not yet definitively know the formation mode of ‘very’ massive stars, and whether the formation involves disk accretion or coalescence of less massive objects. Secondly, there is a possibility that binary evolution already during early core hydrogen (H) burning resulted in the formation of massive blue stragglers (Schneider et al. 2014; de Mink et al. 2014), but the fate of these effectively single VMS will naturally be determined by single-star mass loss.

The existence of the Humphreys-Davidson (HD) limit at approximately solar metallicity tells us that VMS do not become red supergiants (RSG) but that they remain on the hot side of the Hertzsprung-Russell (HR) diagram as luminous O stars and Wolf-Rayet-type objects. For these hot stars the mass loss is thought to be driven by million of iron lines in a radiatively-driven wind, but what is not yet known is whether episodes of super-Eddington (Shaviv 1998), continuum-driven mass loss (such as may occur in Eta Carinae and other Luminous Blue Variable (LBV) star eruptions) may also play a role (see Vink’s Chapter 4 and Owocki’s Chapter 5). What is clear is that the Eddington Γ limit will play a dominant role in the mass-loss physics.

We should also note that the Eddington limit is relevant for another issue relating to VMS physics. When objects approach the Eddington limit, they may or may not *inflate* (Ishii et al. 1999; Petrovic et al. 2006), i.e. be subject to enormous radius and temperature changes (Gräfener et al. 2012). This implies that the temperatures and thus the ages of VMS are highly uncertain.

A final issue concerns the fate of VMS. In the traditional view, after core H-burning, VMS would become LBVs, remove large amounts of mass, exposing their bare-naked helium (He) cores, burn He for another 10^5 before giving rise to H-poor Type Ibc SNe (e.g. Conti 1976; Yoon et al. 2012; Georgy et al. 2012). However since

2006 there have been indications that some massive stars may explode prematurely as H-rich type II SNe already during the LBV phase (Kotak & Vink 2006; Gal-Yam et al. 2007; Mauerhan et al. 2013).

Might some of the most massive stars even produce PISNe? And how do PISNe compare to the general population of super-luminous SNe (SLSNe) that have recently been unveiled by Quimby et al. (2011), and are now seen out to high redshifts (Cooke et al. 2012)? Gal-Yam et al. (2009) discovered an intriguing optical transient with an observed light curve that fits the theoretical one calculated from pair-instability supernova with a He core mass around $100M_{\odot}$ (see also Kozyreva et al. 2014).

Even if the SLSNe turn out to be unrelated to PISNe as argued by Nicholl et al (2013) and Inserra et al. (2013), we should note that alternative models such as magnetar models (e.g. Kasen & Bildsten 2010) would also involve rather massive stars, and if the high luminosity is not the result of a magnetar, but for instance due to mass loss, then the amounts of mass loss inferred for interacting type II SNe are so humongous (of order tens of solar masses; see Smith’s Chapter 8) that they can only originate from VMS.

In summary, the evolution of VMS into the PISN and/or SLSNe regime can only be understood once we obtain a comprehensive framework regarding the evolution and physics of VMS. In this book, a number of experts discuss aspects of their research field relevant to VMS in the local Universe. In Chapter 2 Fabrice Martins discusses the observational data of VMS with a special emphasis on the luminosity and mass determinations of both single and binary VMS. The rest of the book is mostly theoretical. In Chapter 3, Mark Krumholz discusses the different formation modes of VMS. As mass loss is so dominant for the evolution and fate of VMS, the next topics involve the physics of both their stellar winds (Jorick Vink; Chapter 4) and instabilities (Stan Owocki; Chapter 5), before Raphael Hirschi discusses the evolution of VMS in Chapter 6. We finish with an overview of the possible theoretical outcomes in Chapter 7 by Woosley & Heger, and an overview of the observations of VMS fate by Nathan Smith in Chapter 8.

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